Modeling Ancient Settlement Systems with the ENKIMDU Simulation Framework

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Modeling Ancient Settlement Systems

Goals

Examine the dynamics of development and sustainability or demise of settlement systems in both the rain-fed northern and irrigated southern regions of ancient Mesopotamia.

Mesopotamia as testbed for study of long-term human-environment interactions.

Approach

Apply complex adaptive systems, agent-based modeling techniques in a new, holistic simulation framework, to model fine-scale interactions among diverse natural processes and social processes on a daily basis across multi-generational timespans.
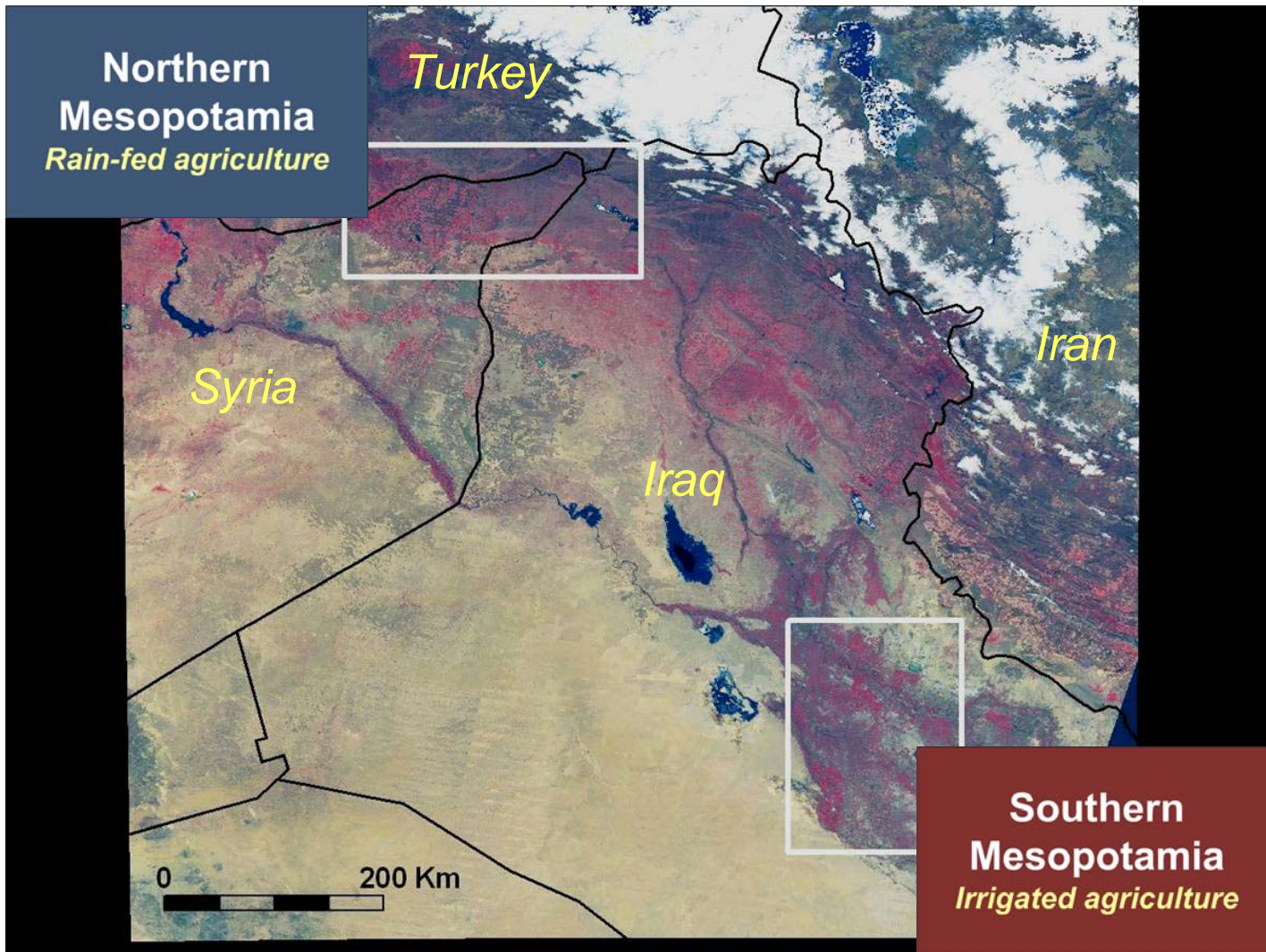
Participants

- The Oriental Institute of the University of Chicago
- Argonne National Laboratory
- The University of Edinburgh (UK)

Support

Five-year National Science Foundation
Biocomplexity in the Environment research grant

Mesopotamian Study Regions

Our Collaborative Development Process

Oriental Institute
of the
University of Chicago

Subject domain data
and conceptual models
derived from:

EXTENSIVE SITE SURVEYS

CENTURIES OF TEXTUAL RECORDS

ETHNOGRAPHY AND CULTURAL ANALOGS

"ENKIMDU"

HOLISTIC AGENT-BASED SIMULATION FRAMEWORK

... named in honor of the ancient Sumerian god of agriculture and irrigation

Argonne National Laboratory
Advanced Simulation Technologies Center

- Computer Modeling and Simulation Expertise
- Advanced Object-Based Discrete Event Simulation Frameworks:

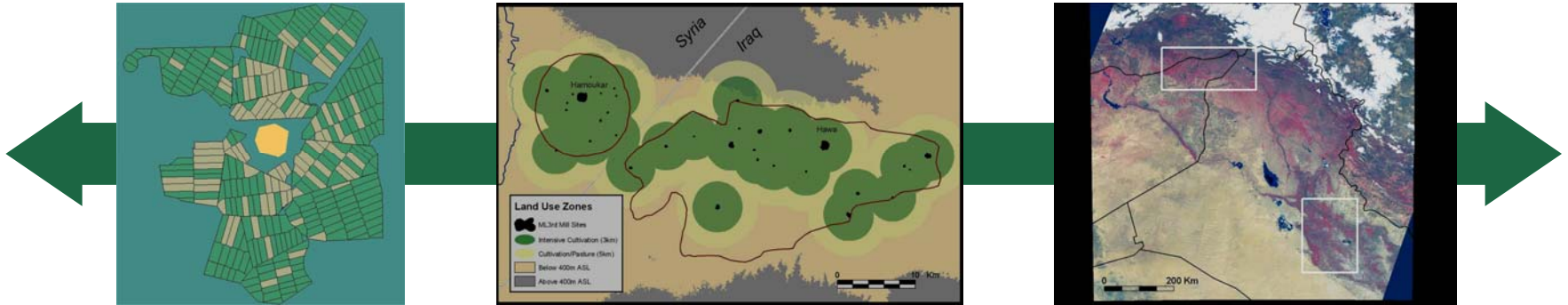**DIAS**
DYNAMIC INFORMATION ARCHITECTURE SYSTEM

A facility for constructing simulations for complex, heterogeneous domains

FACET
SOCIAL SIMULATION FRAMEWORK

A toolkit for constructing models of complex social behavior patterns

Scope and Scale of Simulations

SCOPE: Individual small settlements up to whole regions (> 100 km)

SCALE: *Entity-Level Resolution and Granularity*

- Individual households and persons as independent social agents
- Individual crop fields, domesticated fauna
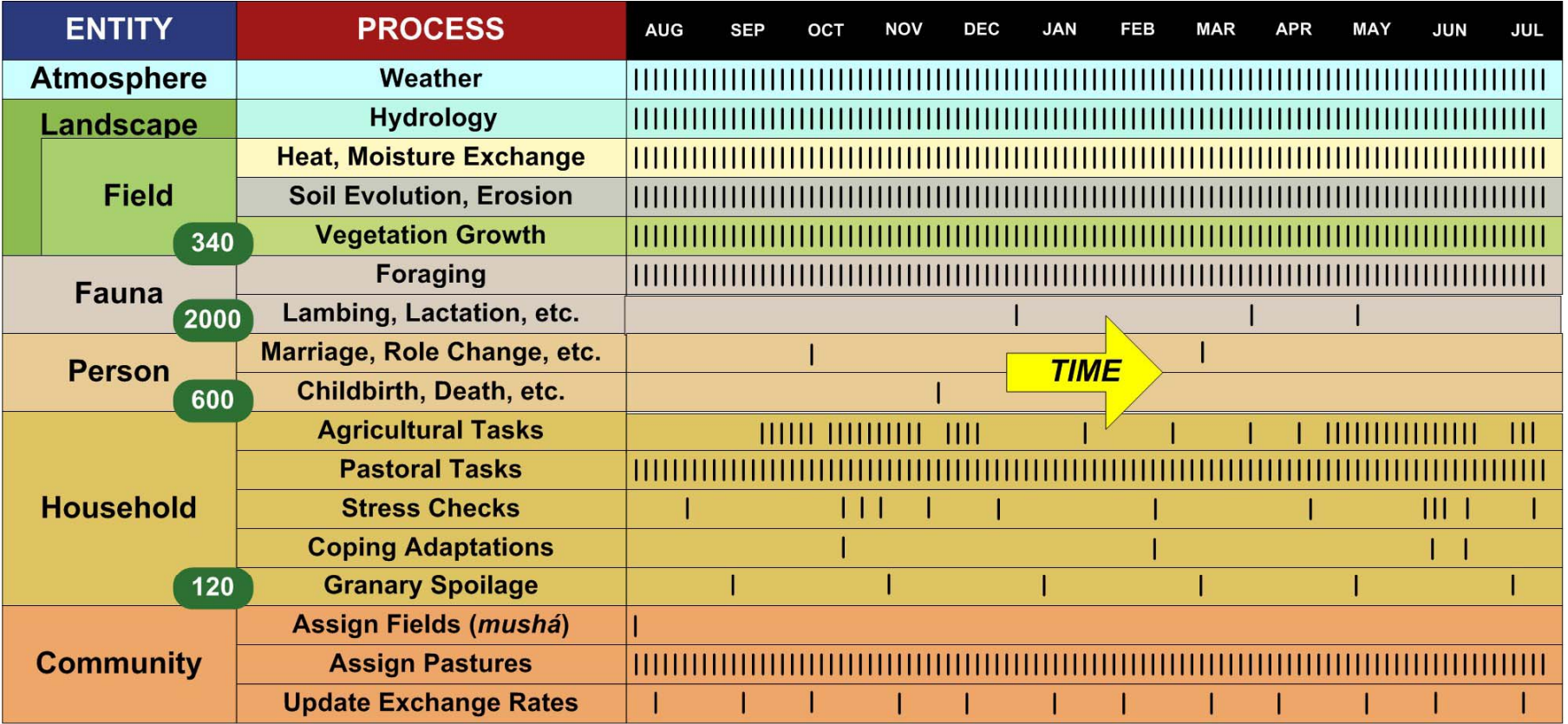
SCALE: *Process and Temporal Resolution*

- Daily weather, hydrologic and soil processes, vegetation dynamics
- Daily to sub-daily (hours, minutes) tracking of detailed household tasks and social interactions

ENKIMDU Object-Based Representation of Key Domain Entities and Their Dynamic Behaviors
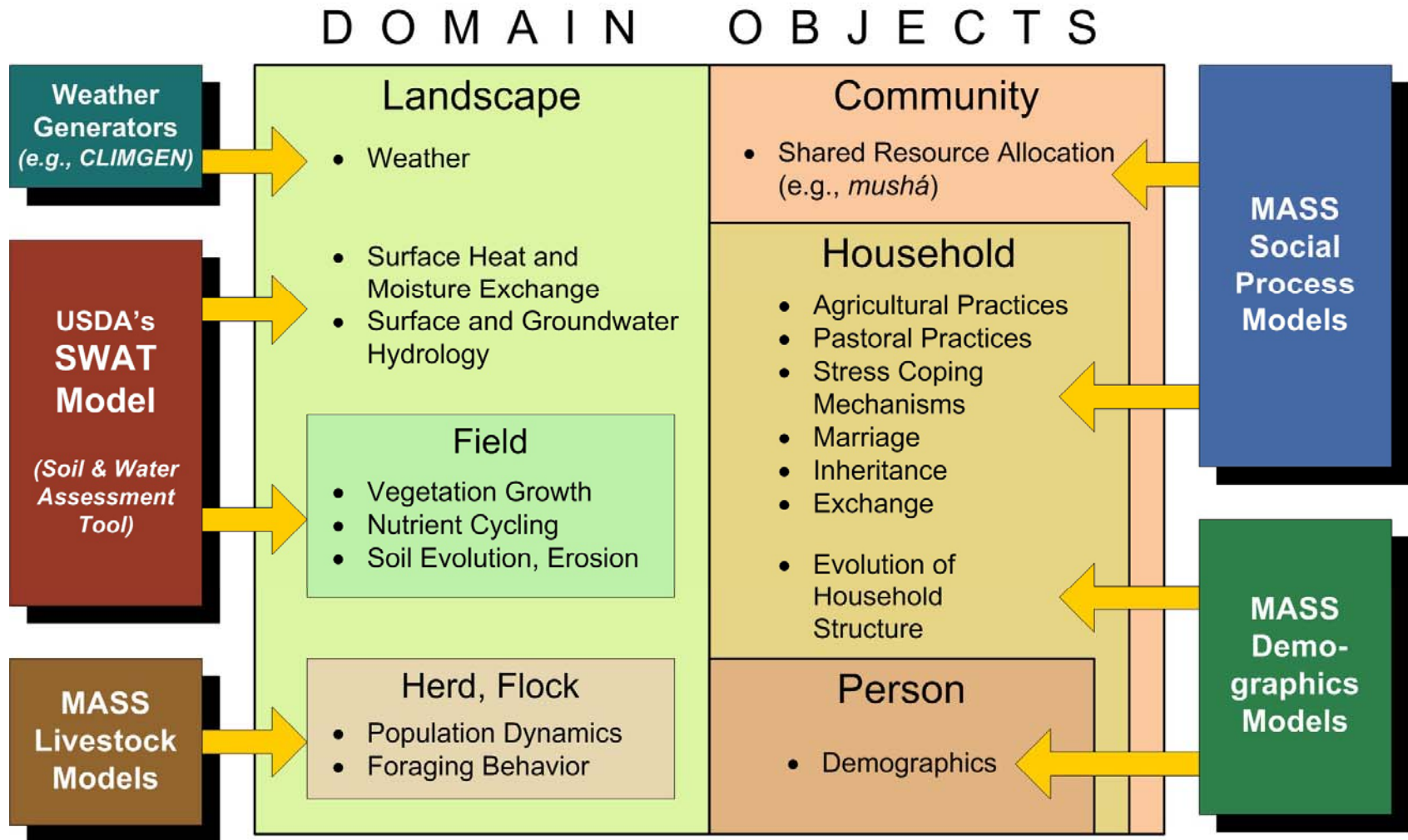
Temporal Texture of Modeled Concurrent Natural and Social Processes

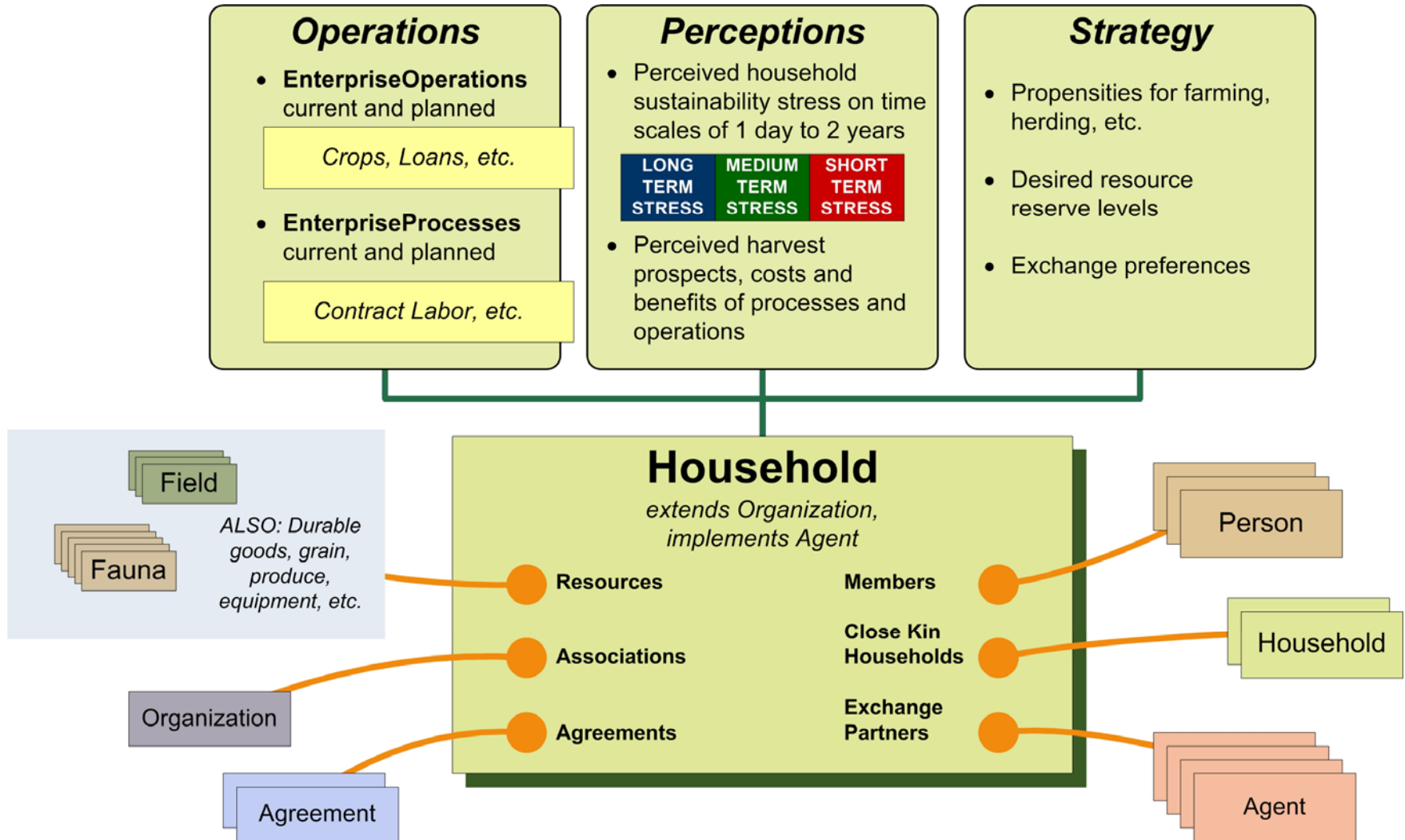| ENTITY		PROCESS	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
Atmosphere		Weather	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
Landscape		Hydrology	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
	Field	Heat, Moisture Exchange	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
		Soil Evolution, Erosion	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
	340	Vegetation Growth	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
Fauna		Foraging	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
	2000	Lambing, Lactation, etc.						I		I	I			
Person		Marriage, Role Change, etc.				I				I				
	600	Childbirth, Death, etc.					I							
Household		Agricultural Tasks		|||||| ||||||||||| ||||	I		I		I		I	||||||||||||	|||
		Pastoral Tasks	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
		Stress Checks		I		I I	I		I			I		I					I		I
		Coping Adaptations			I				I				I I	
	120	Granary Spoilage		I		I		I		I		I		I
Community		Assign Fields (*mushá*)	I											
		Assign Pastures	||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||
		Update Exchange Rates	I		I		I	I		I	I		I		I		I		I		I

TIME →

TICKMARKS INDICATE MODELED INVOCATION OF THE PROCESS BEHAVIOR

N — *Approximate number of instances of this type in the Beydar settlement simulations*

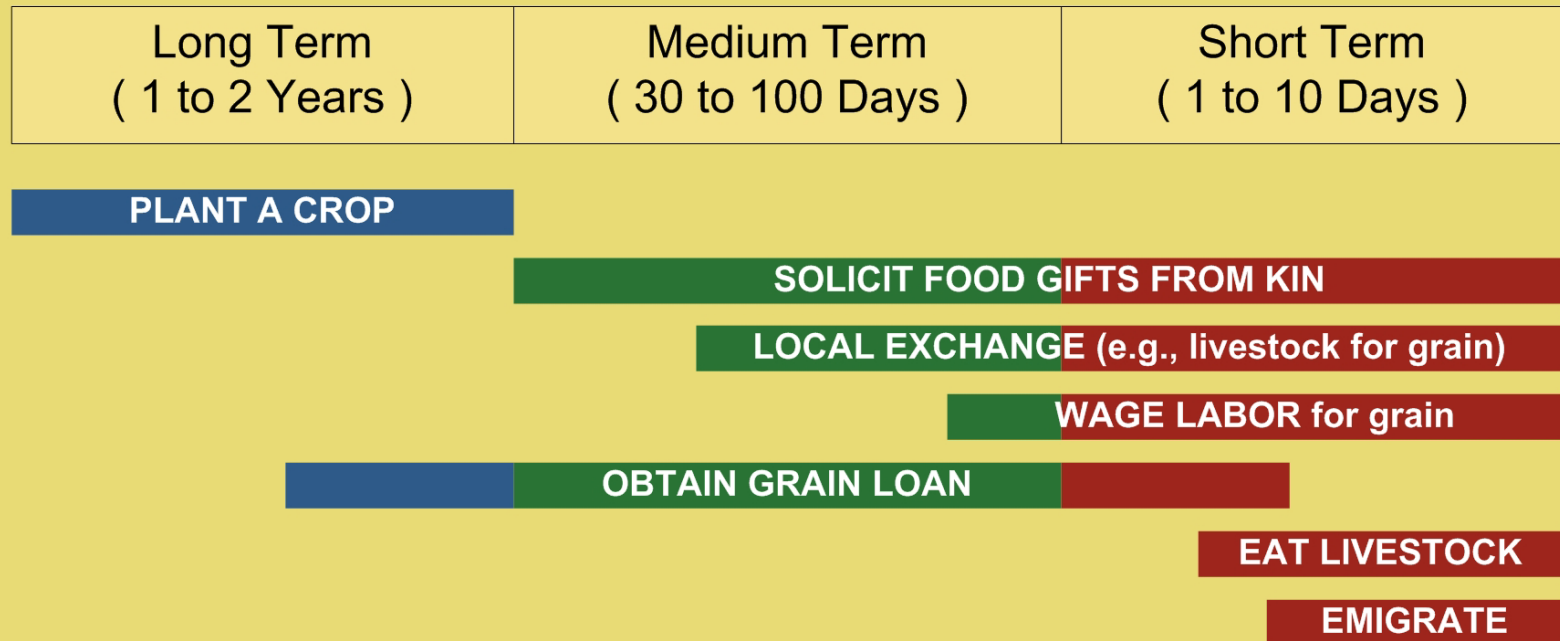# *Example of a Simulated Natural / Social Process Interaction*

Household OBJECT

Field Crop Management Model

Tillage Operations: plow, sow, harvest, etc.

Discrete Time Steps (minutes)

Reported harvest increment amounts, current state of vegetation soil, etc.

Local Herd Management Model

Discrete Time Steps (minutes)

Pastoral Tasks: take herd to and from pasture, etc.

Field OBJECT

Vegetation OBJECT

Landscape OBJECT

SWAT Model
- *Crop growth*
- *Soil evolution*
- *Hydrology*
- *Moisture, energy exchange*

Tillage Events

Updated vegetation and soil states

Grazing Events

Fixed Daily Time Steps

Forage Intake

Grazing Browsing Trampling Manuring

Herd OBJECT

Livestock Forage Models

Discrete Time Steps (minutes)

Here, the Field object is a nexus for process interaction and information flow

Composition of Household Agent Objects

Operations

- **EnterpriseOperations** current and planned

  Crops, Loans, etc.

- **EnterpriseProcesses** current and planned

  Contract Labor, etc.

Perceptions

- Perceived household sustainability stress on time scales of 1 day to 2 years

LONG TERM STRESS	MEDIUM TERM STRESS	SHORT TERM STRESS

- Perceived harvest prospects, costs and benefits of processes and operations

Strategy

- Propensities for farming, herding, etc.

- Desired resource reserve levels

- Exchange preferences

Household

extends Organization, implements Agent

Field

Fauna

ALSO: Durable goods, grain, produce, equipment, etc.

- Resources
- Associations
- Agreements

- Members
- Close Kin Households
- Exchange Partners

Person

Household

Agent

Organization

Agreement

Household Agent Adaptive Behavior Examples

Household agents' perception of sustainability stress can drive them to initiate complex behavior patterns that address different time horizons…

Modeled Household Food Stress Coping Mechanisms

Long Term (1 to 2 Years)	Medium Term (30 to 100 Days)	Short Term (1 to 10 Days)

PLANT A CROP

SOLICIT FOOD GIFTS FROM KIN

LOCAL EXCHANGE (e.g., livestock for grain)

WAGE LABOR for grain

OBTAIN GRAIN LOAN

EAT LIVESTOCK

EMIGRATE

Household preference order for coping responses is top-to-bottom

Exchange

Kin Gifts
- Household Agents can call on their close kin for non-reciprocal assistance.
- Preference order for requests: father, patrilineal uncles, brothers, patrilineal cousins, mother, matrilineal uncles, matrilineal cousins.

Reciprocal Exchange
- Household Agents prefer their established Exchange Partners but will exchange with any other cooperative agent.
- Both parties must perceive a significant benefit in exchanges.
- Exchange rates vary by time and by Market (e.g., Local and Ephemeral Markets).

Wage Labor
- Exchange is reciprocal; day labor is paid each day in grain.

Grain Loans
- Loans due to be repaid in kind, with interest (~ one-third of principal) after next harvest.

Household Agents' Agricultural Behavior Pattern Models

Planting a barley crop: a household coping response to perceived <u>future</u> food stress

Field Crop Management Model

START

WORK CREW — PLOW TEAM

SEED — WORK CREW

FIELD WATER — WORK CREW — Irrigate

FERT-ILIZER — WORK CREW — Fertilize

WORK CREW — Clear And Level

WORK CREW — Plow

Sow — WORK CREW

Maintain Crop — WORK CREW

Harvest — WORK CREW

Wait To Sow

Wait For Next Maintenance Task

Wait To Harvest

KEY: Step | Participant in Step

Most steps are repeatable (next step = this step). All step durations are 1 day or less.

Harvest Disposition Model

First increment of harvest brought to the threshing floor initiates this model

CUEING EVENT

THRESHING FLOOR

Process Harvest — WORK CREW

Dispose Harvest — WORK CREW — GRANARY

These two models are implemented using Argonne's FACET framework

Northern Mesopotamian Pilot Site: Tell Beydar

Early Bronze Age sites, drainage features, and modern political boundaries shown over 30 m resolution digital terrain

Northern Mesopotamian Study Region
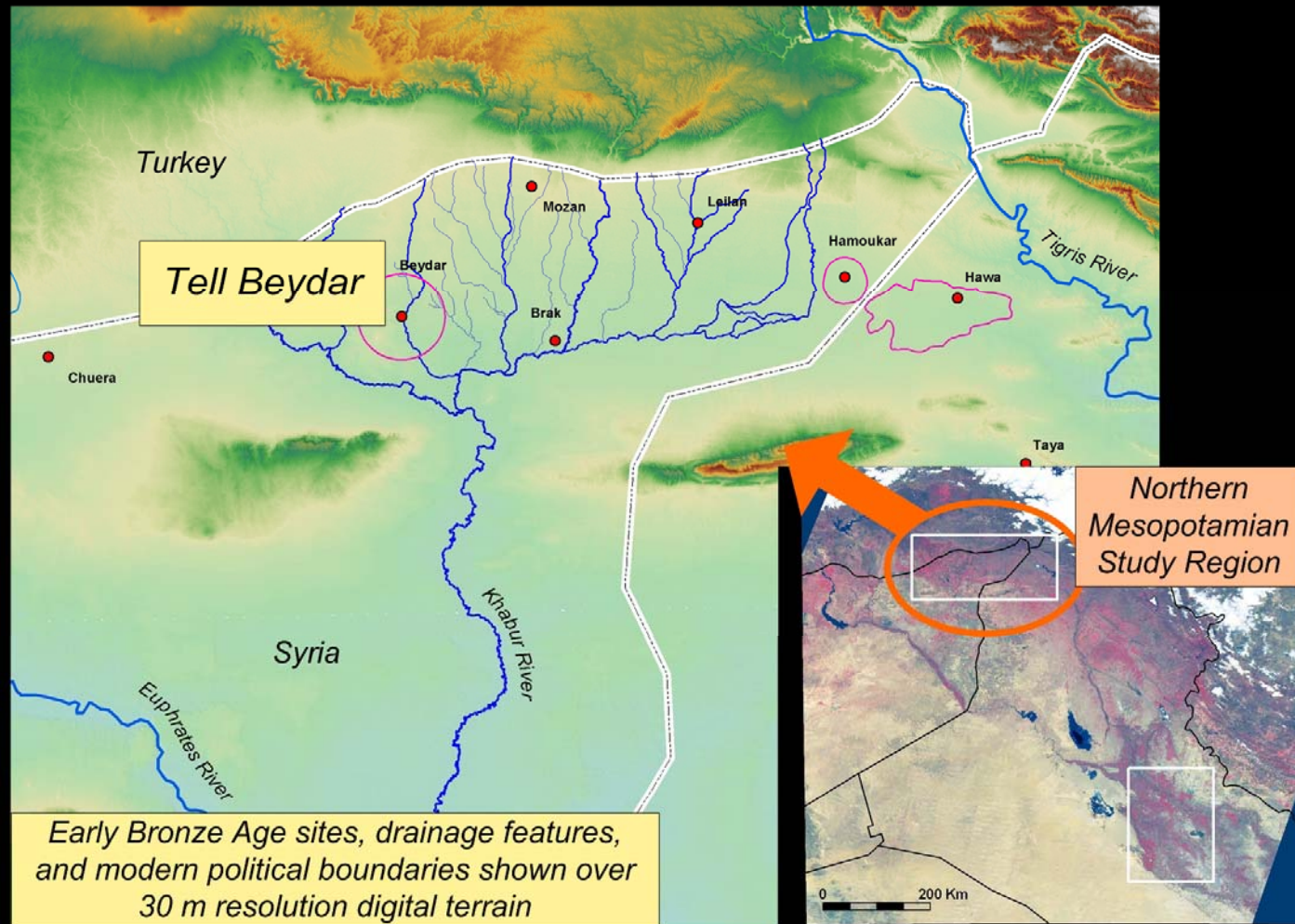
Computer Model of Bronze Age Tell Beydar

A reconstruction based on site surveys and regional analogs:

Tell Beydar Field Layout

Surrounding the Tell Beydar settlement site to a radius of roughly 2 km:

337 fields averaging about 3 ha each → 1,000 ha total

Fields excluded from basalt highlands to west and from courses of major wadis

Soils: calciorthid silty loam; alluvial in wadis; thinly covered basalt formations to west.
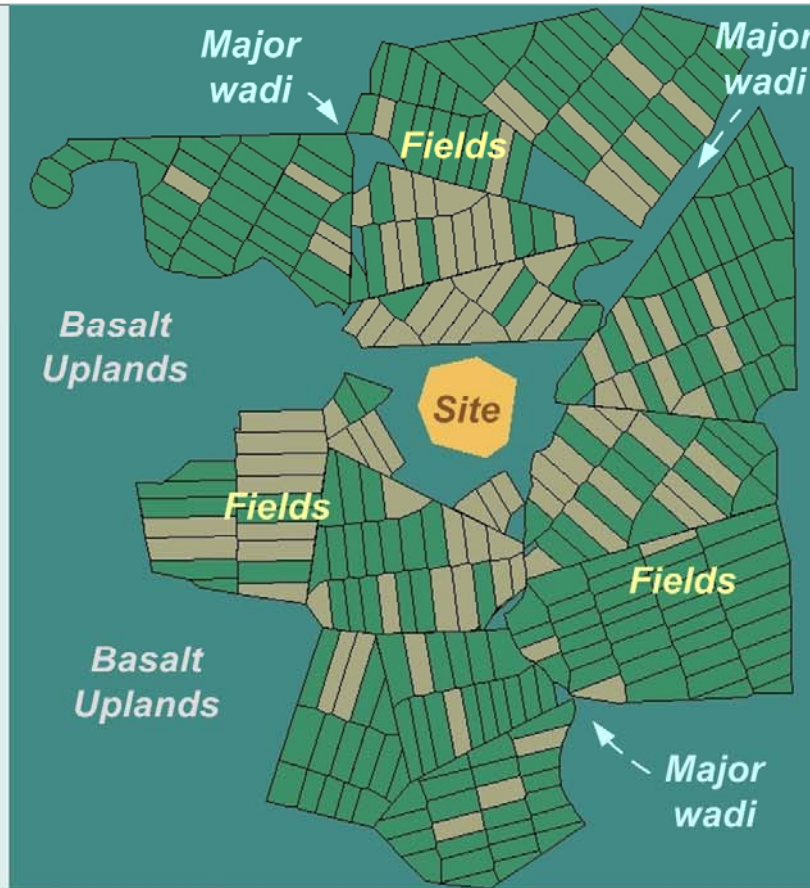
Other Key Data Sources And Assumptions

Weather: 100 years of daily weather synthesized from long-run Mosul, Iraq climatological data.

Crops: Barley only, with botanical parameters adjusted for archaic genotypes.

Livestock: Sheep and goats, with zoological parameters typical of Middle Eastern varieties.

Major wadi · *Major wadi* · *Fields* · *Basalt Uplands* · *Site* · *Fields* · *Fields* · *Basalt Uplands* · *Major wadi*

1   2   3   4   5 km

ENKIMDU's Currently Available Output Streams

Geospatial Animation Displays
Queryable, with zoom, pan, etc.;
fine temporal resolution down to one
simulation minute update interval

Settlement Annals
Nomadic Community Annals
Household Annals
*Summaries of activities by year,
month and/or n-day period,
in Excel spreadsheet format*
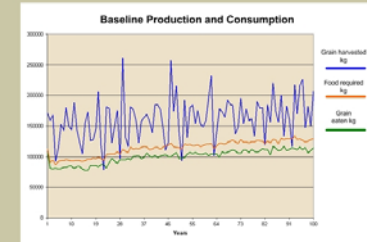
**Ephemeral Market
Summaries**
*Summaries of exchanges by
day and/or for entire market
duration, in Excel
spreadsheet format*

*Ephemeral Market: e.g.,
exchanges between nomads
and townspeople during a
two-week visit to a town by a
nomadic group*

Household Diaries
*Year-by-year chronological
narrative description of all
significant activities of each
household and its members*

Key to Household Diary Results

Household structure and resources at beginning of simulation year (August 1, or Sim Day Number 0)

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 6
Head: carl1(55)   5 Member(s):
Fa: carl1(55) Mo: amanda2(44) Off:(brad9(7) ted7(21) nina8(9))
Close Kin: Br:5 4
Resources: field shares: 3.0 stored grain: 2143.9 kg
                2 sheep

172 > MARRIAGE: ted7(21) has married delilah214(26) /H42

172 > delilah214(26) , new wife of ted7(21) moves in with her
        dependents: xena538(3) lou620(0) zack586(1)

172 > A family unit departs to form a new household:
        Fa: ted7(21) Mo: delilah214(26) Off:(xena538(3)
        lou620(0) zack586(1))

Persons are identified uniquely by randomly assigned name plus integer identifier, with current age in parentheses – here, nina8 is 9 years old

"Embedded" **nuclear families** listed as Father, Mother, (Offspring list)

Close Kin: Household ID numbers of households headed by close kin of this household's head (carl1).

"Outsiders" have /H(household ID Number) appended after their age – thus delilah214 had been a member of Household 42.

HOUSEHOLD NUMBER 21 DIARY FOR YEAR 6
Head: john97(58)   6 Member(s):
Fa: john97(58) Mo: mary98(53) Off:(herman101(12)
ursula103(9) bambi104(10))
gigi100(67)
Exchange Partners: 2 100
Resources: field shares: 2.0 stored grain: 3055.3 kg
                3 sheep   2 goat(s)

"Other" members not part of nuclear families (gigi100 here) are listed last

Exchange Partners: ID numbers of households that have exchanged commodities with this household

Significant events for year, prefaced by Day Number >

• Demographic Events
• Resource Allocation Events

17 > Grain gift of 35.6 kg given to son (H129)

309 > Labor gift of 17.4 person-days given to son (H105)

Here, Household 21 has given **gifts** to Households 105 and 129, which are headed by sons of the household's head, john97

Snapshots from Tell Beydar 100-Year Baseline Simulation: Households' Daily Agricultural and Pastoral Activities
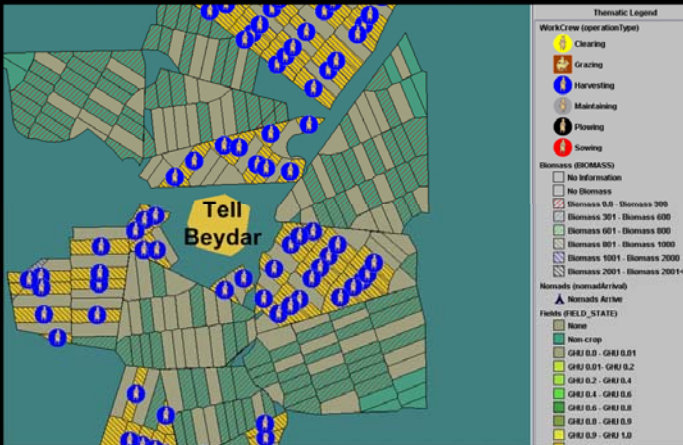
Households' Daily Agricultural and Pastoral Activities - I

Autumn: Field Preparation, Plowing and Sowing

Thematic Legend

WorkCrew (operationType)
- Clearing
- Grazing
- Harvesting
- Maintaining
- Plowing
- Sowing

Biomass (BIOMASS)
- No Information
- No Biomass
- Biomass 0.0 - Biomass 300
- Biomass 301 - Biomass 600
- Biomass 601 - Biomass 800
- Biomass 801 - Biomass 1000
- Biomass 1001 - Biomass 2000
- Biomass 2001 - Biomass 2001<

Nomads (nomadArrival)
- Nomads Arrive

Fields (FIELD_STATE)
- None
- Non-crop
- GHU 0.0 - GHU 0.01
- GHU 0.01- GHU 0.2
- GHU 0.2 - GHU 0.4
- GHU 0.4 - GHU 0.6
- GHU 0.6 - GHU 0.8
- GHU 0.8 - GHU 0.9
- GHU 0.9 - GHU 1.0

Tell Beydar

Households' Daily Agricultural and Pastoral Activities - II

Winter / Early Spring: Weeding, Light Maintenance Tasks
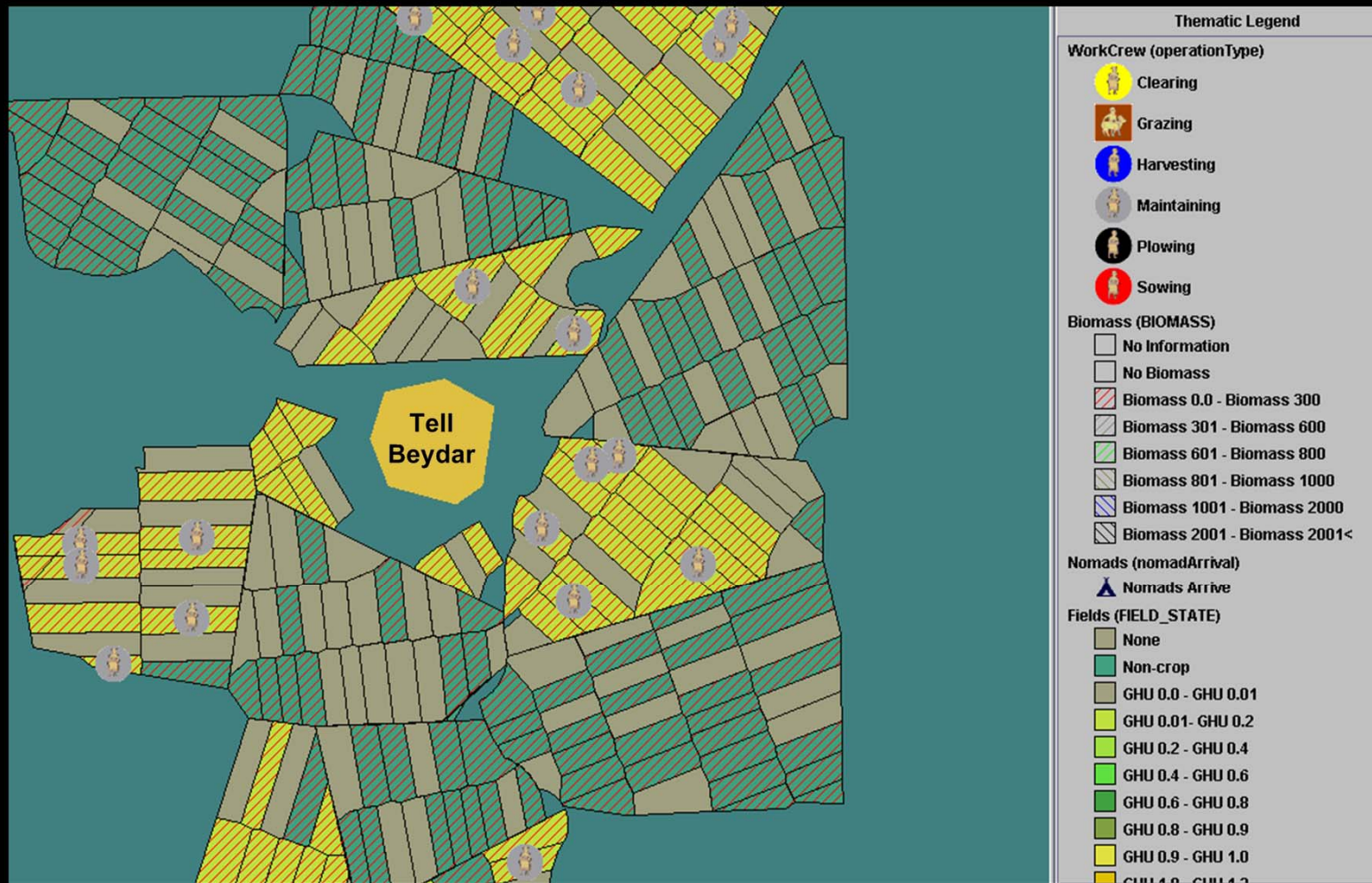
Households' Daily Agricultural and Pastoral Activities - III

Late Spring / Early Summer: Harvest
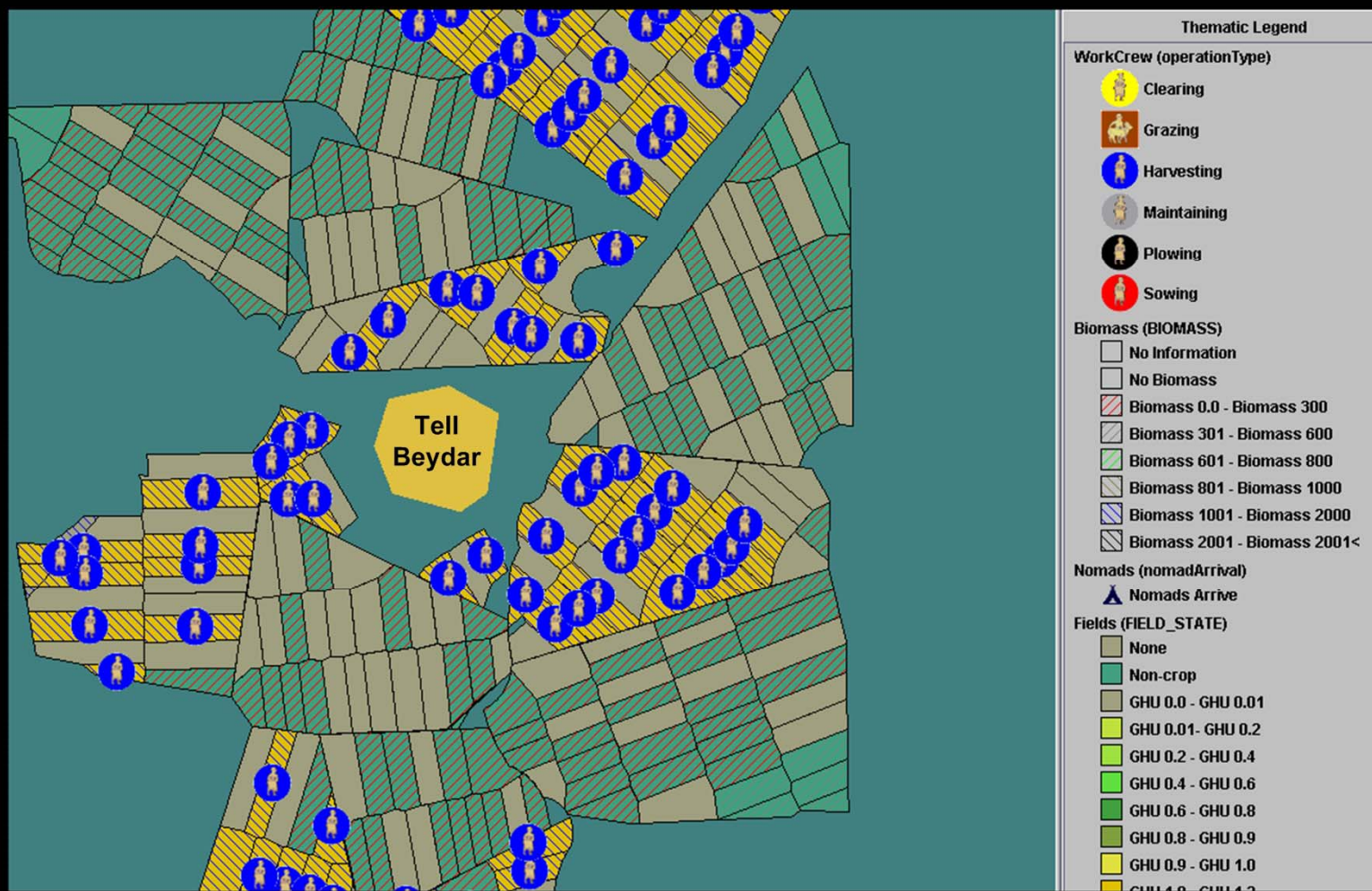
Households' Daily Agricultural and Pastoral Activities - IV

Late Summer: Fields Rest; Grazing Continues
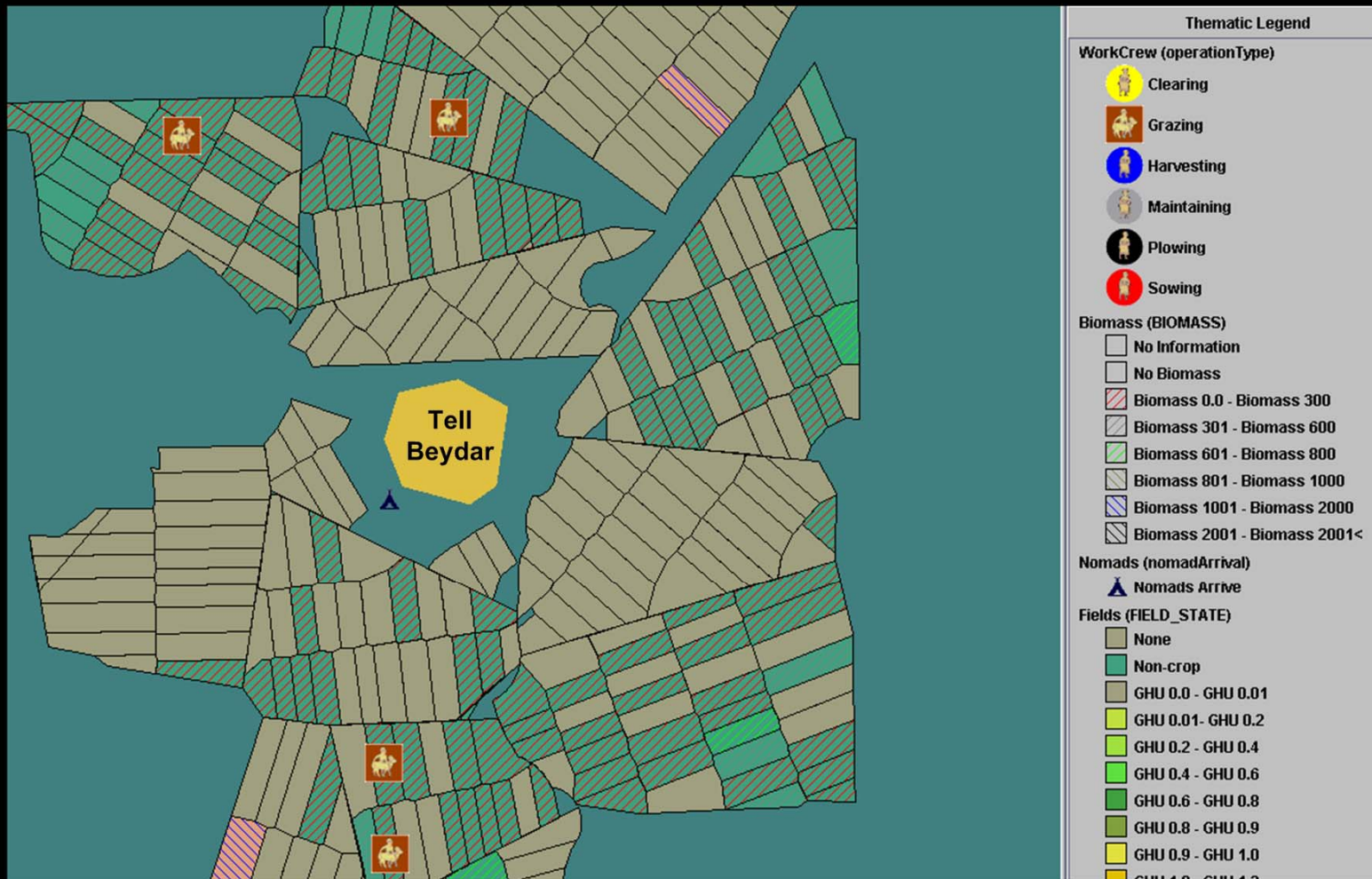
Tell Beydar 100-Year Baseline Scenario

Initial Population: 501 persons in 99 households; 1,188 initial livestock, 12 per household.

Fields allocated to households via *mushá* (community field lottery) system. Biennial fallowing strictly observed by all households. Ard plow or hoe used for tillage.

"Garden of Eden" assumption: no exceptional environmental or societal stresses are imposed.

Baseline Population Dynamics

Baseline Barley Yield and Precipitation
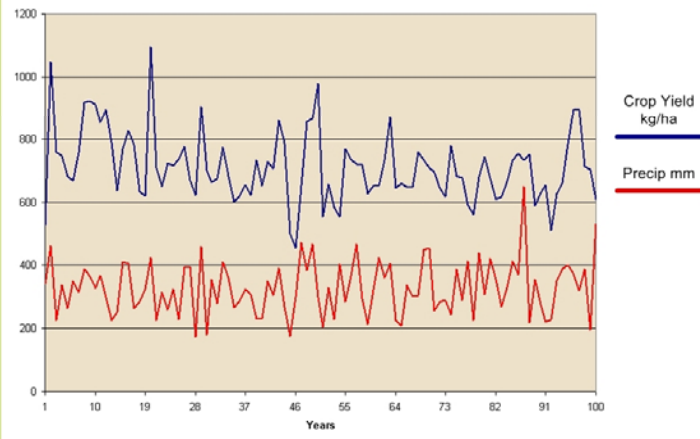
Baseline Production and Consumption
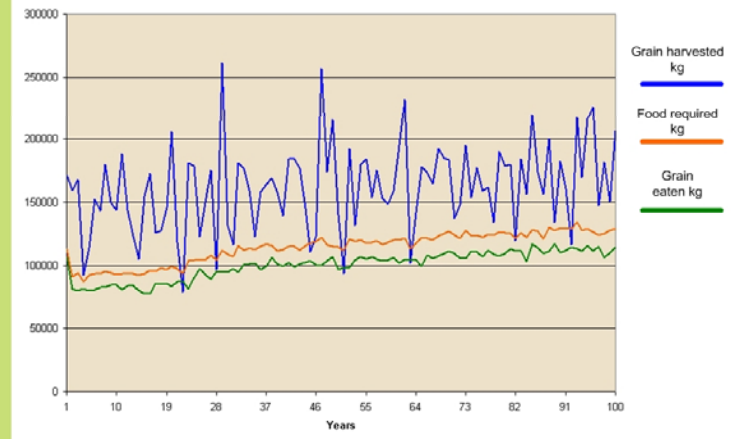
Environmental and Social Stress Scenarios

Scenario Name	Type of Stress	Description of Stress Scenario	Response of Simulated Settlement
Blight	Chronic Environmental Stress	*Recurring harvest blight, variable in space and time*	*Different households affected differently; increased use of exchange-based coping mechanisms*
Drought	Acute Environmental Stress	*Severe 5-year drought*	*Temporary extensification of agriculture to offset reduced yields*
Plow Team Shortage	Chronic Societal Stress	*Farm production bottleneck: plow team availability*	***Abrupt collapse** of settlement as "hidden" critical resource threshold is reached*
Corvee Labor	Acute Societal Stress	*External call for corvee labor: unanticipated labor shortage at harvest time*	*Increase in grain transactions; liquidation of herds; effects felt for many years after corvee episode*
Diphtheria Epidemic	Acute Demographic Shock	*Diphtheria epidemic: sudden decimation of settlement's children*	*Weakening of kinship networks; more non-kin exchanges; delayed shortage of farm labor; **slow decline***

Much more detail is available for these scenarios!

Major Ongoing Project Tasks

- Expand studies to sub-region
  and region scale
  in Northern Mesopotamia

- Implement and test
  Southern Mesopotamian
  pilot settlement model
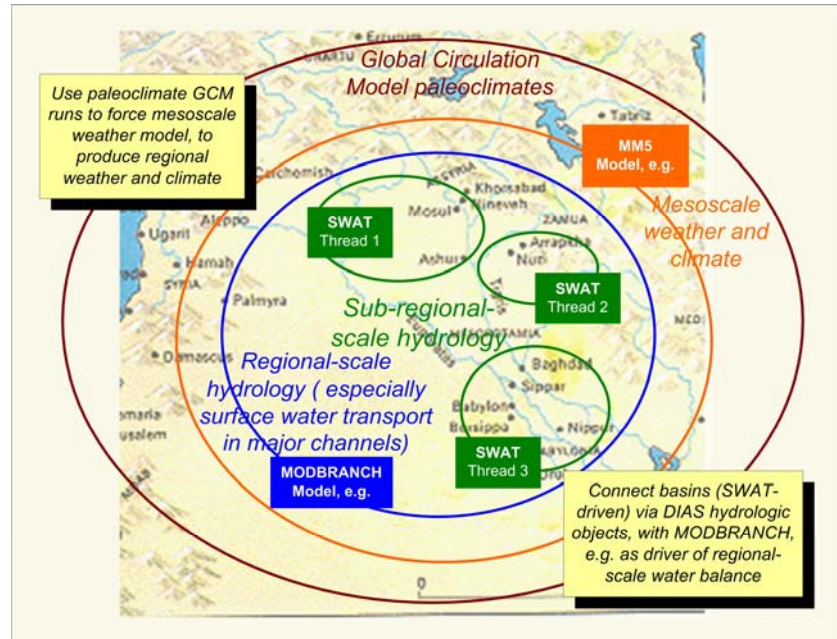
- Strengthen the current agent representation – *e.g.:*

  - stronger person-level (vs. household-level) agency;

  - agent motivations beyond subsistence;

  - emergence and perpetuation of elites

- *New U. of Chicago / Argonne pilot study: modern Thai agroeconomics*

Some Observations

*BUILD MODEL → TEST & RUN MODEL → INTERPRET RESULTS …*

The most scientifically valuable part of this process may turn out to be the model-building phase!

As we attempt to include more and more complex real-world structures and mechanisms within our holistic simulations, we are uncovering more and more knowledge gaps -- technical issues that the scientific community has never before *needed* to resolve, and may never even have *identified* before. Discovering these is a good thing!

It appears that there could be *hundreds* of worthwhile dissertation topics waiting to be discovered in the process of constructing a modeling framework such as ENKIMDU. *(We've found dozens already)*

… And, Finally:
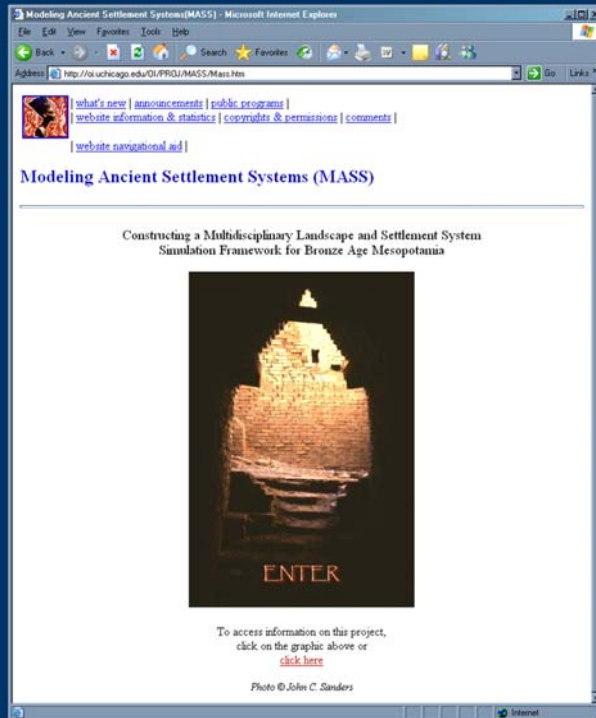
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